EXPERIMENTAL FACILITIES FOR NUCLEAR PHYSICS AND NUCLEAR DETECTION TECHNIQUE

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Performance Calibration Using Cosmic Rays for the Multi-Neutron Correlation Spectrometer*

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Abstract Efficient calibration methods have been applied to a complex neutron detector array by using the cosmic-ray muons. Through a differential operation on the time difference spectrum, the two edges of this spectrum can be precisely determined, corresponding to the geometrical two ends of the bar, and therefore the relationship between the position and time difference spectrum can be deduced for each bar. The alignment between different bars is realized by choosing cosmic-rays which are perpendicular to the bars. The position resolutions are extracted through a track fitting procedure which uses all tracks detected coincidently by the whole system, together with a simulation analysis. A method is also developed to calibrate the deposited energy by using cosmic-rays at different incident angles.

Keywords: neutron detector, calibration, position resolution, deposited energy

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1 Introduction

The development of the facilities for radioactive ion beam (RIB) has provided new opportunities to study the structure and reaction mechanism for nuclei far away from the β-stability line [1,2] . Since the discovery of the halo nuclei, such as ^{11}Li [3∼7] and ^{6}He [8∼11], much attention has been paid to the investigation of the neutron coupling at the surface of the exotic nuclei [12].

Owing to the weakly bounding and large size properties of the unstable exotic nucleus, breakup reactions become a very useful tool to study the nuclear structure [13]. Through kinematically complete measurements of reaction products, including the charged core and the valence neutrons (for neutron rich nucleus), spectroscopic information about the internal structure of the exotic nucleus can be extracted [14]. Therefore performance of the neutron detector array, such as LAND at GSI [15] and MoNA at NSCL [16,17], plays a key role in the experiment. The array should provide accurate position and timing information, and have high detection efficiency together with good cross-talk rejection capability [18]. When more unstable nuclei close to the neutron drip-line are produced, the demand for multi-neutron detection is increased [12].

In order to meet this urgent requirement we are designing and developing a new Multi-neutron Correlation Spectrometer (MunCoS) at forward angles. It consists of 80 scintillation bars (type BC-408), each having a size of 200 cm× 5 cm × 5 cm and connected to two photo-multiplier tubes (PMT, type Hamamatsue R1828-01) at both ends. An efficient and precise calibration method using cosmic rays is applied and presented in this paper.

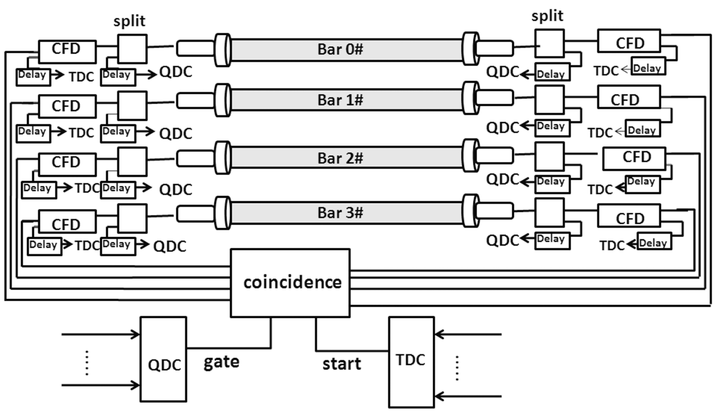

Fig.1 A schematic view of the test setup

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The test setup is a standing frame which can support up to six (actually only four are used) scintillation bars with a vertical spacing of 17 cm (Fig. 1(a)). Cosmic ray muons with high energies of a few GeV are used in the test experiment. For each hit to a scintillation bar, timing and deposited energy (t and Q) are recorded for the two ends. For a straight bar the exponential attenuation of the light signal along the bars is well satisfied [19]. Therefore the average energy loss for each bar could be defined as:

$$Q = \sqrt{Q_{\mathrm{L}} * Q_{\mathrm{R}}}, \tag{1}$$

where Q is the geometric mean of the left and right side signals Q_{L} and Q_{R}, respectively. The horizontal position is determined by the difference of the two timing signals taken from both ends.

2 Position determination

When a muon hits a scintillation bar, light signals will be generated and propagate to the two ends. Time difference of the two signals varies with the hitting position. Normally the position calibration can be done by placing and moving a collimated gamma-ray source along the scintillation bar, and recording the time difference accordingly. However, this method is time consuming and not practical for a complex array like MunCoS. A more elaborate method was developed which allows to calibrate several bars and all positions at the same time by using the cosmic-ray.

Firstly we assume that the time difference is linearly dependent on the position. This is approved by many previous measurements [15~17] and also by the current measurement which generate a flat spectrum (Fig. 2(a)) for time difference when irradiated by uniformly distributed cosmic-rays. Then based on the linear correspondence between the geometrical two ends of the bar and two edges of the spectrum, the relationship between the time difference and the position can be deduced. Of course the accuracy of the relationship relies on the precision in determining the spectrum edges. Fortunately the edges are very sharp as shown in Fig. 2(a). Quantitatively, the edges can be precisely determined by applying a differential operation to the time difference spectrum, as illustrated in Fig. 2(b), and taking simply the peak positions. To verify this edge determination method, a Monte-Carlo simulation was carried out which generates signals uniformly along the bar and smeared according to the detector performances. The simulated differential spectrum is shown in Fig. 2(c), and two peaks are very well superposed on the geometric ends with an error less than 1 cm. From the positions of two edges (U_{edge} and D_{edge}) on the time difference spectrum (Fig. 2(b)) and the length L of the bar, the linear relationship between the position along the bar y (cm) and the time difference $\triangle t$ (channel) can be easily determined as:

$$y = (\triangle t - D_{\mathrm{edge}})/(U_{\mathrm{edge}} - D_{\mathrm{edge}}) \times L, \tag{2}$$

or in a linear form of $\triangle t$:

$$y = L/(U_{\mathrm{edge}} - D_{\mathrm{edge}}) \times \triangle t - D_{\mathrm{edge}} \times L/(U_{\mathrm{edge}} - D_{\mathrm{edge}}). \tag{3}$$

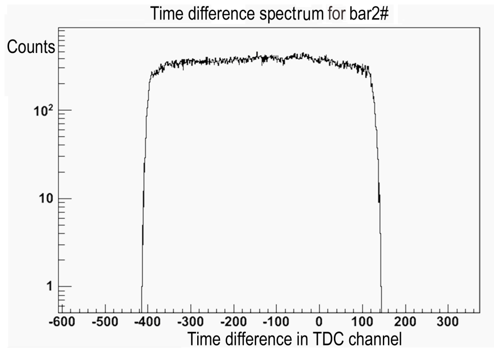

Fig.2(a) Time difference spectrum for bar2# in the cosmic ray test. The time is expressed in TDC channels

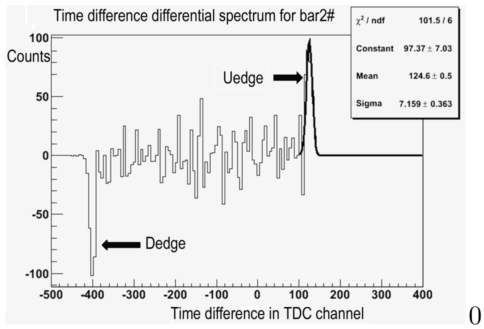

Fig.2(b) Differential spectrum based on the spectrum in Fig. 2(a). Two edges are now displayed by the peak positions

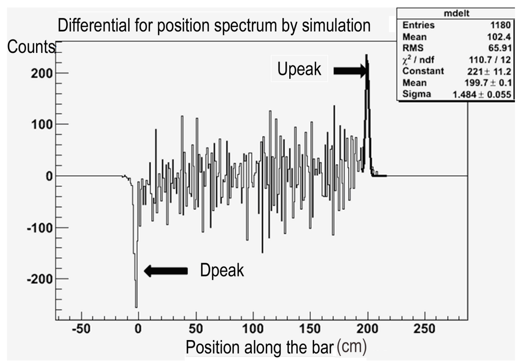

Fig.2(c) A simulated position differential spectrum for bar2# from a differential operation on its position spectrum in simulation. Two peaks (D_{peak}, U_{peak}) very close to the geometric ends, 0 cm and 200 cm, can be seen clearly. A Gaussian fit to the U_{peak} is shown in this figure, with a peak value of 199.7 cm

3 Alignment of the whole system

From formula (3), the hitting position for each bar in its internal coordinate system is obtained from time difference spectrum. But for a detector array composed of several bars, the alignment is needed before applying them to measure a cosmic ray track. The manual operation could result in a geometrical uncertainty of a few centimeters and therefore an inherent method is required to set the offsets for each bar in order to put the whole setup in a unified coordinate system.

When a muon track passes perpendicularly through two misaligned scintillation bars, bar1# and bar2# or instance as illustrated in Fig. 3, each bar will give a measured position in its internal coordinate system from formula (3), $y1$ and $y2$ respectively. The difference $\triangle y$ is right equal to the offset d of the bar2# relative to the bar1#. The question is how to choose the perpendicular tracks. In reality we need to choose two bars (often the uppermost one and the lowest one) as the common reference bars which are manually aligned as precisely as possible. The perpendicular cosmic-ray tracks are then selected by putting narrow cut on the position of these two bars for the coincidently measured events. Other bars are then added into the coincidence and the narrow position spectrum for each test bar can be used to set its offset relative to the common reference bars. Adding the offset value into formula (3) for each bar, a unified coordinate system is well established for the whole setup. It should be noted that the reference bars themselves may have a little misalignment problem, but this will introduce only a small error for the direction of the track but not affect the determination of a straight line by the setup.

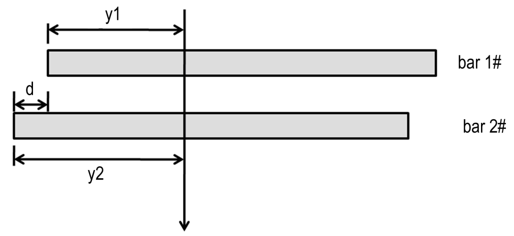

Fig.3 An illustration of a muon track passing perpendicularly through the bar1♯ and bar2#. The offset d can be obtained by $d = y2 - y1$

4 Position resolution

Normally people use two very small trigger scintillators installed above and below a test scintillation bar to set a reference position. The position resolution of the test bar can then be obtained by analyzing the coincidently measured position spectrum of the bar. The spectrum has a position spread relative to the width of the trigger scintillators, from which the resolution can be extracted. This method generally requires very long time for the calibration of a large system. We use a new approach based on measurement of all cosmic-ray tracks passing through the whole system without any limitation of small trigger detectors. For each coincidently recorded event, a straight line can be obtained by a linear fit to the four hitting points on the four bars. Then the distance between the actual measured position and the fitted line is recorded for each bar as its actual residual. This procedure is repeated for all coincident events, regardless of its actual position along the bar. The residuals for each bar can then be accumulated and plotted as shown in Fig. 4(a), which reflects the quality of position resolution of the corresponding bar. A relationship between the σ_1 of the residual distribution from a Gaussian function fit and the real detector position resolution σ_e of the bar can be found by a Monte-Carlo simulation with the same detector setup.

In the simulation the "measured position" for each bar is calculated from the real hitting position of a generated track smeared by an uncertainty corresponding to a preset σ_e. A linear fit is applied to these simulated "data" and the corresponding "residues" are accumulated to generate the simulated σ_1, exactly the same way as for the real experimental data. By changing the σ_e in the code and repeat the simulation, a linear relationship between σ_e and σ_1 is obtained and presented in Fig. 4(b). From this relationship, the actual position resolution for each bar can be extracted as listed in Table 1. It is seen that the detector position resolution (FWHM) for each bar is about 3 cm, which is excellent for this kind of large scintillation bar. Of course this resolution is an average value along a bar which is supposed to have a good uniform quality.

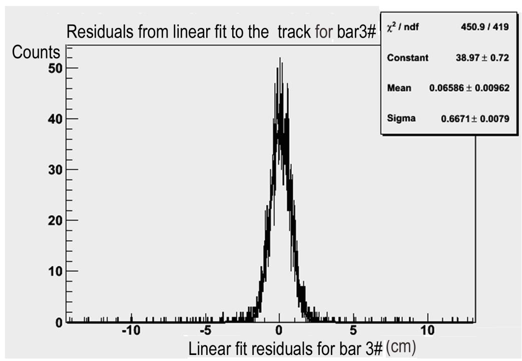

Fig.4(a) Distribution of residuals (defined in section 4) for bar3#. A Gaussian function fit gives the standard deviation σ_1 of 0.7 cm

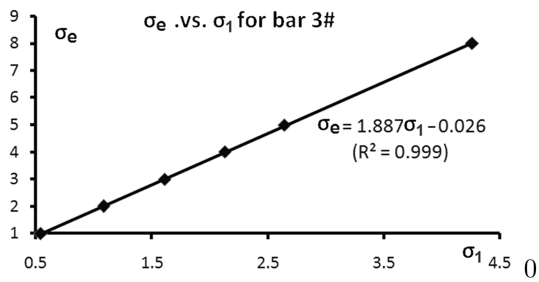

Fig.4(b) The relationship between σ_e and σ_1 for bar3# from the simulation, which can be described by a linear function as the solid line in the figure. Similar results are also obtained for other scintillation bars

Table 1. Position resolutions extracted from σ_1 of the residual distribution

Bar number	σ_1 (cm)	Relationship between σ_1 and σ_e	σ_e (cm)	FWHM* (cm)
0#	0.7	σ_e=1.869σ_1-0.009	1.3	2.9
1#	1.1	σ_e=1.266σ_1-0.064	1.3	3.1
2#	1.0	σ_e=1.254σ_1-0.032	1.2	2.9
3#	0.7	σ_e=1.887σ_1-0.026	1.2	2.9

*Position resolution (FWHM) is associated with σ_e by a factor of 2.355

5 Calibration of the deposited energy

Energy deposited in a scintillation bar in neutron detection is an important quantity for applying some cross-talks (CT) rejection technique in a multi-neutron detection experiment [20]. The charge Q in a signal taken by a PMT is recorded by a QDC channel. Q is in general proportional to the deposited energy ΔE:

$$Q = a \times \triangle E + b. \tag{4}$$

To determine the calibration coefficients a and b, one needs to inject various charged particles with known energies into the scintillator, and measure the Q values accordingly. Here we take the advantage of the cosmic-ray muons at different incident angles to conduct the calibration for limited energy range.

The energy loss per unit length $\mathrm{d}E/\mathrm{d}x$ of a high energy muon in a plastic scintillation counter is almost a constant [21], about 2.0 MeV ee(equivalent electron energy)/cm. If the incident angle is θ, relative to the axis perpendicular to the bar, the energy loss on the bar becomes:

$$\Delta E = (-\mathrm{d}E/\mathrm{d}x) \times L = (-\mathrm{d}E/\mathrm{d}x) \times h/\cos\theta, \tag{5}$$

where h is the thickness of the bar. Substituting formula (5) into (4), we find:

$$Q = a \times (-\mathrm{d}E/\mathrm{d}x) \times h/\cos\theta + b = C/\cos\theta + D, \tag{6}$$

with $C = a \times (-\mathrm{d}E/\mathrm{d}x) \times h$ and $D = b$, both being constants.

The data used in section 2, 3 and 4 are from the same test measurement. They can also be used to determine C and D. All recorded events are divided into several groups according to the incident angle. A range of incident angle from 0 to 60 degrees with an interval of 5 degrees is chosen. For each angular interval, Q values (in channel) of the events are accumulated, and the mean Q for this angle interval is obtained from a Laudau function fit to the accumulated distribution. The linear fit to Q versus $1/\cos\theta$ is shown in Fig. 5. The description is well satisfied.

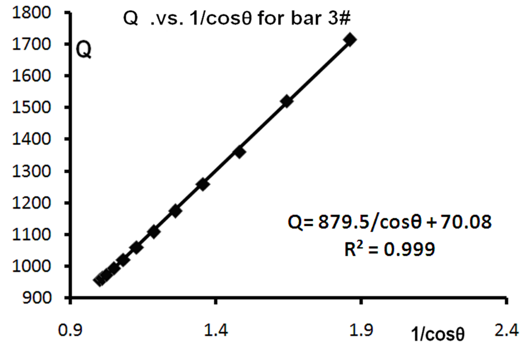

Fig.5 Linear relationship between the amplitude of energy loss signal Q and $1/\cos\theta$ for bar3#. Similar results are also obtained for the other three bars in the test, with a correlation coefficient of about 0.999

The absolute value of $\mathrm{d}E/\mathrm{d}x$ has been measured to be 2.0 MeV ee/(g$\cdot$cm^2) [22]. With a density of 1.032 g/cm^3 and a thickness of 5 cm for the current bars, constant a (in Channel/ MeV ee) in formula (4) can be deduced from C as:

$$a = C/(10.32 \text{ MeV ee}), \tag{7}$$

while constant b is right equal to D (in channel).

6 Summary

Efficient calibration methods have been applied to a complex neutron detector array by using the cosmic-ray muons. Through a differential operation on the time difference spectrum, the two edges of the spectrum can be precisely determined, corresponding to the geometrical two ends of the bar. The relationship between the position and time difference spectrum can therefore be deduced for each bar. The alignment between different bars is also realized by choosing cosmic-rays which are perpendicular to the bars. The position resolutions are extracted through a track fitting procedure which uses all tracks detected coincidently by the whole system, together with a simulation analysis. This is a very efficient way compared to the traditional hardware collimation method. We have also developed a method to calibrate the deposited energy by using cosmic-rays at different incident angles.

References

1 Ershov S N, Grigorenko L V, Vaagen J S, et al. 2010, J. Phys. G, 37: 064026

2 Suzuki Y, Lovas R G, Yabana K, et al. 2003, Structure and reaction of light exotic nuclei. Taylor and Francis, London

3 Tanihata, Hamagaki H, Hashimoto O, et al. 1985, Phys. Rev. Lett., 55: 2676

4 Kobayashi T, Yamakawa O, Omata K, et al. 1988, Phys. Rev. Lett., 60: 2599

5 Shimoura S, Nakamura T, Ishihara M, et al. 1995, Phys. Lett. B, 348: 29

6 Nakamura T, Vinokumar A M, Sugimoto T, et al. 2006, Phys. Rev. Lett., 96: 252502

7 Ieki K, Sackett D, Galonsky A, et al. 1993, Phys. Rev. Lett., 70: 730

8 Cortina-Gil M, Roussel-Chomaz P, Alamanos N, et al. 1997, Phys. Lett. B, 401: 9

9 Alkhazov G D, Andronenko M N, Dobrovolsky A V, et al. 1997, Phys. Rev. Lett., 78: 2313

10 Wang J, Galonsky A, Kruse J J, et al. 2002, Phys. Rev. C, 65: 034306

11 Ye Y L, Pang D Y, Jiang D X, et al. 2005, Phys. Rev. C, 71: 014604

12 Hagino K, Sagawa H, Schuck P. 2010, J Phys G, 37: 064040

13 Shyam R, Chatterjee R. 2003, Breakup Reactions Of Drip Line Nuclei. lectures in the workshop on “Nuclei at Extremes of Isospin and Mass”

14 Simon H, Meister M, Aumann T, et al. 2007, Nucl. Phys. A, 791: 267; Dickhoff W H. 2010, J. Phys. G, 37: 064007

15 Blaich Th, Elze Th W, Embling H, et al. 1992, Nucl. Phys. A, 314: 136

16 Luther B, Baumann T, Thoennessen M, et al. 2003, Nucl. Inst. and Meth. A, 505: 33

17 Baumann T, Boike J, Brown J, et al. 2005, Nucl. Inst. and Meth. A, 543: 517

18 Nakamura T, Vinodkumar A M, Sugimoto T, et al. 2006, Phys. Rev. Lett., 96: 252502

19 Grabmayr P, Hehl T, Stahl A, et al. 1998, Nucl. Inst. and Meth. A, 402: 85

20 Sackett D, Ieki K, Galonsky A, et al. 1993, Phys. Rev. C, 48: 118

21 Leo W R. 1994, Techniques for nuclear and particle physics experiments. Springer-Verlag, New York

22 Luther B, Baumann T. 2002, MoNA Manual, Michigan State University, USA

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